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Effect of the Oxides as a Pinning Center Doping to the Bi-2212 Single Crystal

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***Abstract*— It is important to form pinning centers in superconductors to allow the flow of large currents through the specimens. To clarify the properties of pinning centers, it is preferable to investigate single crystals. Critical current (Ic) of the $Bi_2Sr_2CaCu_2O_x$ (Bi-2212) single crystal is increased by doping the oxides. The condition of heat treatment for doping the oxides as a pinning center is 400°C, 5h in the conventional method. There is a possibility that the pinning center formation and the Ic will be changed by increasing the time of the heat treatment for doping.**

***Index Terms*— Pinning center, Single crystal, Bi-2212 Superconductor, Oxide doping.**

I. INTRODUCTION

It is necessary to trap magnetic flux at pinning centers in superconductors to allow the large currents to flow through the specimens. To trap magnetic flux, it is effective to form pinning centers by doping with non-superconducting particles. Many researchers have studied pinning centers using bulk superconductors [1-3]. However, there are insulators or grain boundaries which can act as pinning centers in bulk samples. So, to clarify the properties of pinning centers, it is desirable to dope single crystals. This eliminates the effects of boundaries between grains.

In this study, we used the heat treatment to dope single crystals of $Bi_2Sr_2CaCu_2O_x$ (Bi-2212) with Al_2O_3 and measured the critical current (Ic). The doping depth of Al_2O_3 is controlled by the time of heat treatment. It is possible to investigate the effect of the the density and the defuse length of the pinning center from the single crystal surfaces to critical currents.

II. EXPERIMENT

Single crystals of $Bi_2Sr_2CaCu_2O_x$ (Bi-2212) were prepared by the self-flux method [4]. Starting materials were prepared by mixing and grinding powders of Bi_2O_3, $SrCO_3$, $CaCO_3$ and CuO in the compositional ratio, Bi: Sr:Ca:Cu=2:2:1:2. The mixed powders were put into alumina-crucibles with a cap and they were heat-treated in an electric furnace. Figure 1 shows the temperature profile of crystal growth in this study. In the first growth phase, the samples were heated at 960ºC for 10 hours. They were slowly cooled to 800ºC at a rate of 1 ºC /h. The single crystals prepared by the first growth were grounded, and they were put into the alumina crucibles again.

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The heating and cooling procedure were repeated. The critical temperature (Tc) of a prepared single crystal was about 80K.

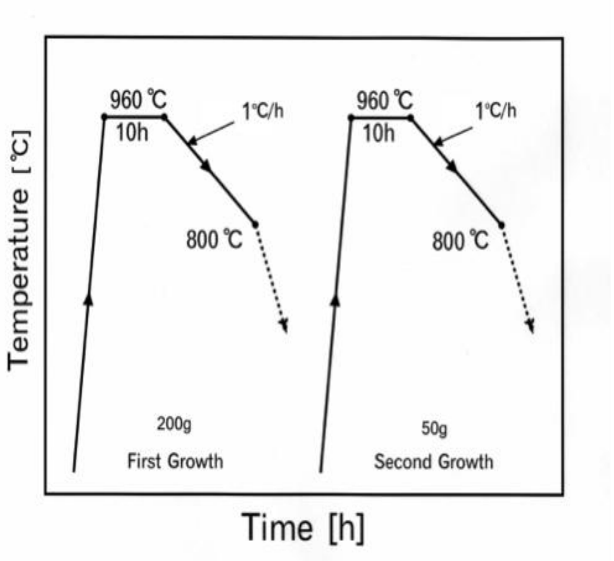

Fig. 1 The temperature profile of Bi-2212 single crystal growth in this study

Oxides were doped onto the surface of Bi-2212 phase superconducting single crystals using the heat treatment. As shown in Figure 2, single crystals were placed on the powders of oxides Al_2O_3, and heated at 400ºC. The oxides were diffused into the crystals. The time of the heat treatment for doping the oxides was 1 hour, 5 hours and 40 hours. After the heat treatment for doping, Au electrodes were formed by Au ion sputtering and the heat treatment of 400ºC for 5 hours. Single crystals were processed into a plate-like shape used by adhesive tape and a sharp cutter. The surface layer of the single crystal was reduced up to 30 µm by the process. By cleaving the surface several times, the under layer of the single crystal became a new surface layer. The critical current Ic of Bi-2212 single crystals as measured by the four-probe method did not increase linearly with an increasing thickness of the crystal. The Ic of the samples was measured as a current per width of 1 cm (Ics) at 77K. The saturated Ics value was about 2.8A. The results were that the current flow in the a-b plane was different from that in c-axis in an oxide superconductor with the layered structure [5]. The resistance-temperature (R-T) characteristics of the samples and their current-voltage (I-V) characteristics at 77K were measured by four-probe method.

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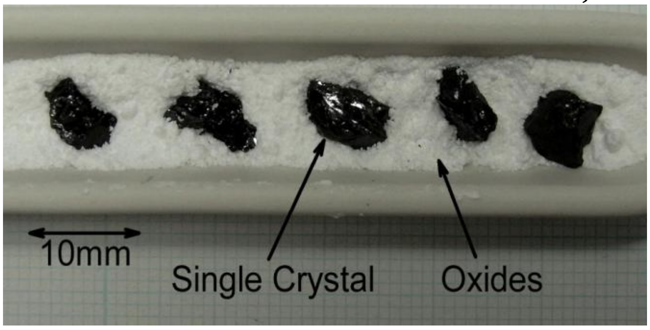

Fig.2 Photo image of Bi-2212 single crystals on the powders of oxides. The oxides were diffused into the single crystals by heat treatment.

III. RESULTS AND DISCUSSION

Tc of the single crystal doped with Al_2O_3 for 5h was 82.2K. Generally, the Tc of a Bi-2212 phase superconductor is around 80K so the single crystal doped with Al_2O_3 has a similar value. This result indicated that the chemical composition of the superconducting phase was not changed by Al_2O_3 doping. The Tc of the single crystals doping with the other doping time did not change. The result suggested that the oxide doping by the heat treatment did not affect the chemical composition of prepared single crystals.

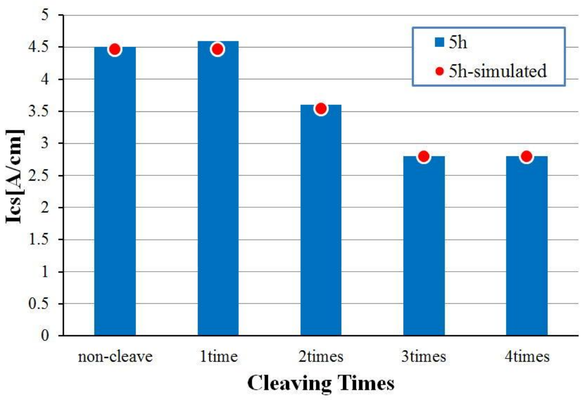

Fig.3 Ics of Al_2O_3 doped for 5h into the Bi-2212 single crystal

Figure 3 shows the Ics of single crystals doped with Al_2O_3 by heat treatment for 5h. The Ics of the single crystals was changed by the cleaving times. In the single crystal of doping Al_2O_3, the Ics of non-cleaved single crystals is 4.5 A/cm. The Ics was not changed by cleaving the surface only one time. They indicated that the surface under 30μm formed the same pinning centers. The surface cleaved two times, the Ics of the single crystal decreased to 3.6A/cm. This was caused by the decrease of the density of pinning centers on the surface. Cleaving the surface over three times, the Ics of the single crystal was saturated to 2.8A/cm. The Ics was similar to that of pure Bi-2212 single crystal. The results indicated that the pinning center was not defused over 90μm.

Figure 4 shows the model of the pinning center defused into the Bi-2212 single crystal [6]. We calculated the Ics by doping models to analyze the current conduction mechanism. Lp was the length of the pinning center, which was defused into the single crystals. In the model, the density of the pinning center was not changed from the surface to Lp. In this layer, the superconducting critical current was increased by the pinning centers. The current flow from the surface was limited to the c-axis [7]. The current flow under the surface was smaller than the top surface. The total Ics was given by the following equation.

$$I_{cs} = I_{csf} \cdot \sum_{l=0}^{\infty} \alpha(l)\, x^l \qquad (1)$$

Here, α was the amplitude parameter by the pinning center. The layer of the Bi-2212 single crystal was cleaved, taking off 30μm each time. By increasing the amount of cleaving, the superconducting current flows came into existence in the layer with the pinning center and pure single crystal area. The total Ics was decreased by the flows of the layer of these areas.

Figure 3 shows the results of measured and simulated Ics of the single crystals by the doping of Al_2O_3. We simulated the Ics value by the models. The parameters of A and Lp were changed to attach the experimental results. In figure 3, we attached the model with the properties A=1.6 and Lp=66μm. The Ics value was consistent with the experimental value. The results indicated that the pinning center existed about 66μm deep from the single crystal surface with the same density and in a porous shape.

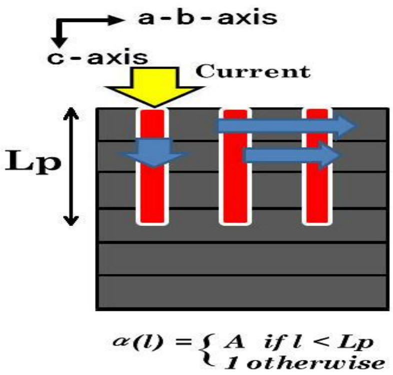

Fig.4 Model of the pinning center defused into the Bi-2212 single crystal.

Figure 5 shows the measured and simulated Ics of the single crystal by doping for 1h. The Ics of the surface cleaved one time was 4.0 A/cm. The value was smaller than that of the single crystal doped for 5h. They indicated that the density of the pinning center of the single crystal by doping for 1h was smaller than that by doping for 5h. We attached the Ics with the pinning model with A=1.45 and Lp=63μm.

Figure 6 shows the measured and simulated Ics of the single crystal by doping Al_2O_3 for 40h. The Ics was shown around 9.0 A/cm for the single crystal surface non-cleaved and the surfaces cleaved up to four times. The value was two times as large as that of the single crystal doped for 5h. They

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indicated that the density of the pinning center of the single crystal was increased by increasing the doping time. The mmeasurement value was not stable due to the increase of doping time. However, the Ics was not changed by cleaving the surface four times and decreased by doing it five or six times. These results suggested that the defuse length of the pinning centers formed under the surfaces was over 180μm. We attached the Ics with the pinning model with A=3.09 and Lp=192μm.

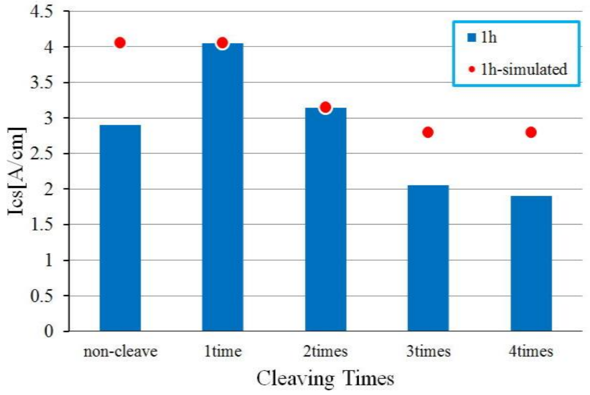

Fig. 5 Ics of Al_2O_3 doped for 1h into the Bi-2212 single crystal

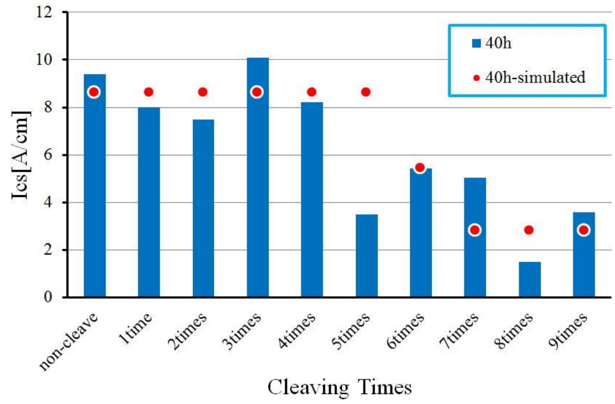

Fig. 6 Ics of Al_2O_3 doped for 40h into the Bi-2212 single crystal

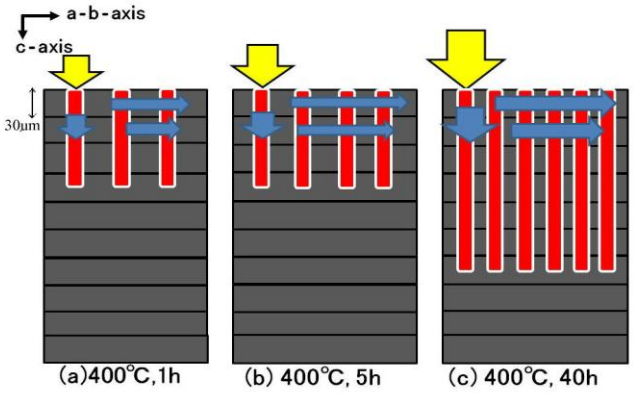

Fig.7 Model of the pinning center defused into the Bi-2212 single crystal for each times.

Pinning centers were defused to Bi-2212 single crystals by heat treatment. The Ics of the single crystal was changed by the doping time. The density of the pinning center which was doping oxides was changed by the doping time. The defuse length from the single crystal surface was also changed by the doping time. Therefore, figure 7 is the doping model of the pinning center defused to the layer of the Bi-2212 single crystals.

IV. CONCLUSION

Al_2O_3 was doped onto the surface of Bi-2212 single crystals by the heat treatment. The time of the heat treatment for doping the oxides was changed from 1 to 40 hours. The particles were diffused into the single crystal and they acted as pinning centers. The critical current of the samples was improved by doping oxides. The Ics of the Bi-2212 single crystal was 2.8 A/cm. Compared with the untreated single crystal, the samples of doping Al_2O_3 for 5h showed the Ics values of 4.5 A/cm and of doping for 40h displayed Ics of 9 A/cm. The oxides were doped from a crystal surface to the depth of 190μm in the 40h doped sample. By increasing the doping time, the density of the pinning center of the single crystal surface was also increased. The results indicated that it was effective to use oxides to create pinning centers in superconducting single crystals. The doping time was the parameter of the density and the defuse length of the pinning center from the single crystal surfaces.

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Hiroya IMAO completed his master's degree in Technological University of Nagaoka in 1988, and then became a research associate in the Department of Control Engineering at Matsue National College of Technology. He became an Associate professor in 1999 and later a Professor of National Institute of Technology, Matsue College in 2013. Ph. D. (Eng).